CONSULTANT REPORT

PIER
Public Interest Energy Research
CALIFORNIA ENERGY COMMISSION

Strategic Energy Research

LIGHT-ACTIVATED SURGE PROTECTION THYRISTOR (LASPT)

Gray Davis, *Governor*

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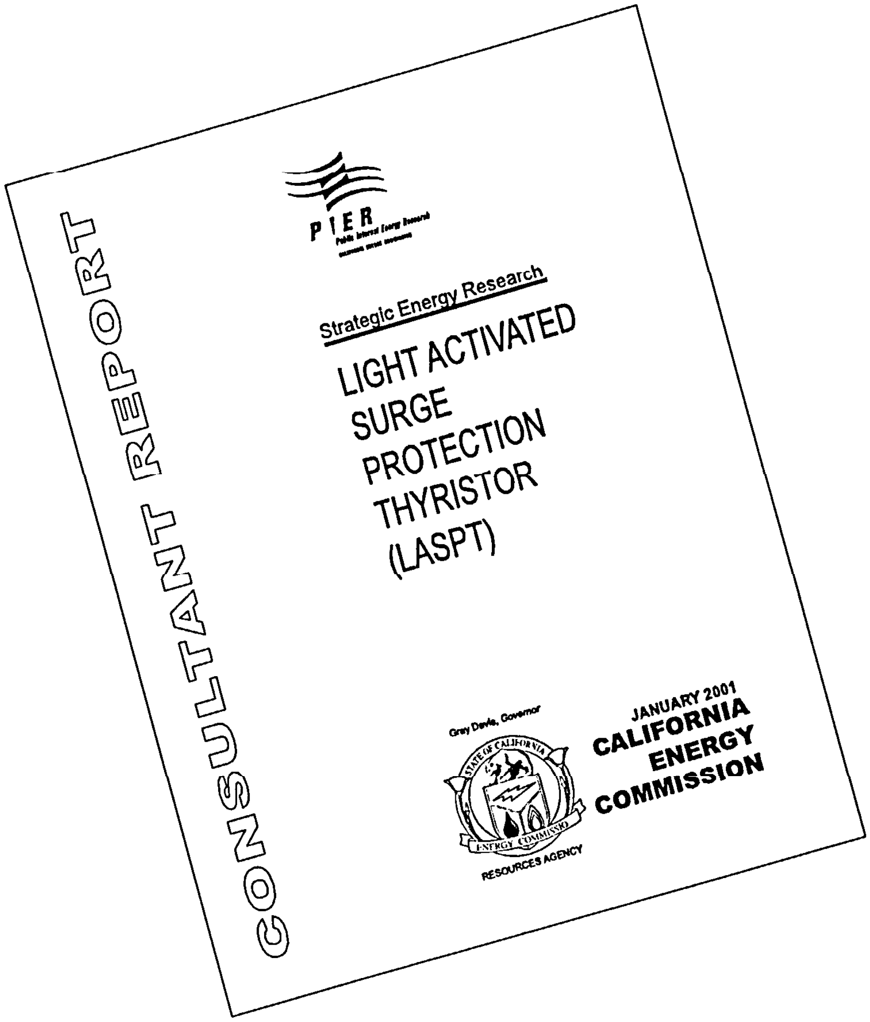

CALIFORNIA ENERGY COMMISSION

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Legal Notice

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million through the Year 2001 to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Environmentally-Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Strategic Energy Research

In 1998, the Commission awarded approximately $17 million to 39 separate transition RD&D projects covering the five PIER subject areas. These projects were selected to preserve the benefits of the most promising ongoing public interest RD&D efforts conducted by investor-owned utilities prior to the onset of electricity restructuring.

What follows is the final report for the Light Activated Surge Protection Thyristor (LASPT) program, Contract Number 500-98-038**,** conducted by OptiSwitch Technology Corporation, San Diego, California. The report is entitled Light Activated Surge Protection Thyristor. This project contributes to the PIER Strategic Energy Research program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

Introduction

The electricity system in California is vulnerable to large-scale power disruptions due to rapid power surges resulting from lightning or mechanical failures. These rapid surges cannot be fully mitigated by the existing surge protection devices in power plants and the transmission and distribution systems. The economical cost of these power failures amounts to more than $1 billion dollars a year.

The overall goal of this project was to develop a surge protection device with a response with an order of magnitude faster that systems currently used by the electric power industry. Many current surge protectors employ a switch known as a thyristor that is activated by electrical current. Our goal was to develop a prototype of a Light Activated Surge Protection Thyristor (LASPT) that would respond much faster than current activated thyristors.

Objectives

Project objectives were to:

- Develop a LASPT prototype with a much faster response than current activated thyristors.
- Design, fabricate, and demonstrate the superior performance of a LASPT device to current activated units.
- Determine the target unit price for production of LASPT devices

Outcomes

Under this project we developed a prototype LASPT device. Table 1 summarizes the specific performance objectives required by the contract and the actual experimental results achieved.

Table 1. Performance Objectives vs. Results

LASPT Parameter	Required Under Contract	Measured in this program	Percentage Increase
Blocking Voltage	2,700 volts	4,400 volts	63%
Peak Current	15,000 amperes	47,000 amperes	213%
Rate of Rise of Current	10,000 amperes/ microsecond	52,000 amperes/ microsecond	420%

As can be seen in the table, the measured voltage, peak current, and rate of rise of current is respectively a factor of two, three, and five times greater than those required.

Based on the breakdown of the production processes, we concluded that in a production volume of several hundred units, the fabrication cost would be $1,200 per device. This cost could go down to approximately $700 per unit for high volume production. Achieving this cost estimate requires further engineering development of: (1) a 1.1-micron laser diode. (2) a glass based optical coupling system, and (3) a robust production package.

Conclusions

The superb technical performance obtained in this project, and the initial production cost estimates indicate that we can fabricate cost effective LASPT devices that contribute to Public Interest Energy Research (PIER) program objectives.

Benefits to California

The installation of LASPT devices contributes to the PIER program objective of improving the reliability of the California electricity system by lowering the vulnerability of the electric power producers and users to power outages resulting from rapid surges. Because it required high-risk scientific and technical development, successful demonstration of an LASPT device also contributed to the PIER Program's strategic energy research objectives, which include:

- Design and fabrication of a custom made thyristor.
- Development of a unique method to illuminate a large area of the thyristor.
- Development of a laser source to couple the light into the thyristor.

The scientific success of this project enables production of cost effective LASPT-based surge protection systems. In addition we are considering incorporating LASPT technology into the following systems:

- Inertial fusion energy power plant being developed by the U. S. Navy using U.S. Department of Energy (DOE) funding.
- Electric motor control devices being developed by Rockwell International.

Both of these applications will benefit California electric power producers and users.

Recommendations

The next steps in this project should be continued development in the three areas mentioned above (1.1-micron laser diode, glass based optical coupling system, and robust production package) as well as demonstration LASPT device performance in a system application. Three such systems under considerations are:

- Surge protection systems in electric power plants
- Control devices in electric motors
- Pulse power drivers for an inertial fusion energy plant

Abstract

Under this project we designed an innovative Light Activated Surge Protection Thyristor (LASPT) using a proprietary technique to couple a laser light source to a large of area of the thyristor. A prototype LASPT device was fabricated and its performance was characterized. With a voltage blockage of 4,400 volts and a current of 47,000 amperes, the rate of rise of current was 52,000 amperes per microsecond in a 50 mm diameter device. This response time is approximately 50 times larger than the state-of-the-art thyristor and higher than the current program technical objective by a factor of five. Installing such devices in electric power plants and power distribution centers will protect the California electric system from power failures resulting from high power surges caused by lightning or equipment malfunctioning. These power failures cause damages in the billion of dollars annually, both to power producers and power users.

Key Words: thyristor, light activation, surge protection

1.0 Introduction

1.1 Background

The interconnectedness of regional energy systems makes California's electrical power producers and users vulnerable to large-scale power disruptions from rapid surges that cannot be fully handled by existing electrical distribution system protection devices. The limiting factor in providing 100 percent reliability of the electrical distribution system is the present day technology of surge protection devices. The best commercially available thyristors being used in surge protection devices can only handle current surge rates less than 2000 amperes per microsecond.

While these devices can handle a large portion of the unwanted transients, they do not provide 100 percent system reliability. This is especially true in instances of fast high power surges caused by lightning strikes or equipment malfunctions,[1] such as the extensive 1996 electrical distribution disruption in the western United States caused by a power line fault in the Pacific Northwest. Billions of dollars are lost each year to high power line faults.

Current and voltage transients in electrical distribution systems are handled routinely in the United States today with transmission line surge arresters constructed with some form of metal oxide varistor blocks.[2] Arresters limit voltage transients, by conducting current when voltages rise above normal limits. Hundreds of thousands of arresters are in use today, especially in lightning-prone areas, where "flashovers are by far the most frequent cause of transmission line outages".[3] Surge arresters also suppress high magnitude switching surges and power line faults.

Lightning alone causes power outages that cost utilities more that $1 billion a year in damaged or destroyed equipment and replacement power.[3] Cost estimates for the damage due to switching surges, and other power line faults, are easily double this amount. The interconnectedness of regional energy systems makes California electrical users vulnerable to large-scale power disruption from rapid surges that cannot be fully handled by existing electrical distribution system protection devices.

1.2 Project Objectives

It is the objective of this project to design and build an innovative Light Activated Surge Protection Thyristor (LASPT) prototype that provides an order-of-magnitude improvement in current surge response rates over existing devices. Wide spread use of such devices would effectively prevent cascading power failures from rapid surges while increasing the reliability of California's electrical power supply to all residential, industrial, commercial, and agricultural users.

To design and build a prototype LASPT device requires a significant scientific and engineering development, in particular in coupling radiation from multiple optical fibers to a silicon substrate to achieve large area activation with laser light. Under the PIER Strategic Energy Research Program, the completion of this high risk LASPT prototype will directly lead to an end product of long-term high benefit to all California electricity users. Because of the high-risk nature of the research, the optical coupling is not currently under development nor is it provided for by competitive or regulated markets.

While surge protection devices are rated by several parameters, the key parameters are maximum voltage, maximum current, and the rate-of-rise-of-current (dI/dt) that the devices can handle.[4,5] Current and voltage ratings for higher power systems can be achieved by adding multiple devices in parallel or series configuration. State-of-the-art semiconductor protection devices are limited by current technology in their ability to increase the rate of rise of current (dI/dt). Although higher dI/dt devices are being sought for numerous applications, there is no technology available today that meets Public Interest Energy Research this demand.

The specific technical and economical objectives of this project were to develop and demonstrate a light activated thyristor with the following performance parameters:

Blocking Voltage	2,700 volts
Peak Current	15,000 amperes
Rise of Rate of Current	10,000 amperes/microsecond

As it is important to fabricate such devices at a price the industry can afford. Thus, the economical objective of this project is to:

- Estimate fabrication cost of a high performance light activated thyristor.

The high-risk scientific and engineering optical coupling objectives, achieved in this project, enable not only LASPT production, but also numerous other devices for power quality and supply, and industrial electrical applications. These applications include flexible alternating current transmission systems (FACTS), high power uninterruptible power supplies (UPS), static switches, synchronous rectification, traction drives, induction heating, and high voltage direct current systems.[6] The payoff to California electricity users will be higher reliability in electrical service, advanced devices across a wide range of application based on the new technology, and increased employment in the manufacturing light activated thyristor products.

1.3 Report organization

Section 2.0 describes our technical approach to develop the LASPT device in order to achieve our technical and economical objectives. In Section 3.0 we summarize the outcome of the project, both the performance of the LASPT, and the cost of fabrication. For the convenience of the reader we provide detail technical information in appendices rather than in the main text of the report. And in Section 4.0, based on the outcome of the project, we discuss the conclusions of our work and we recommend specific steps on how to proceed.

2.0 Project Approach

The overall objectives of this project were to:

- Design and fabricate a high performance LASPT device
- Measure its performance
- Estimate its fabrication cost

This section consists of three sub-sections. In subsection 2.1, we describe our approach to designing a custom made high performance LASPT device. In subsection 2.2 we outline the test equipment used and our measurement techniques. Finally, in subsection 2.3 we provide details of the methodology used to estimate the fabrication cost of LASPT devices.

2.1 Design of a Custom LASPT Device

To assure a fast response of the LASPT, it is important to illuminate a large area of the thyristor. We accomplished this by designing a proprietary custom designed thyristor, with special openings to enable the illumination of a large area; a laser light source; and an efficient optical coupling device to transmit the energy from the light source to the thyristor. Our approach to the design and fabrication of these three elements is discussed in the following sections.

2.1.1 Thyristor Design

We designed the LASPT primarily using a two dimensional device simulation code called Medici, which is sold and supported by Avant! Corporation. We designed a series of optical openings to couple the light into the device. The openings were intended to illuminate 50 percent of the device, while not reducing the blocking voltage by more than 10 percent. OptiSwitch Technology Corporation (OTC) successfully designed the LASPT with the following characteristics:

Blocking Voltage	4.2 kilo volts (3.4% reduction over non-treated device)
Peak Current	17.9 kilo amperes
Rate of Rise of Current	17.9 kilo amperes per microsecond
Temperature Rise	13° C

Note these are not maximum numbers. The temperature rise would be greater for higher current. Appendix I contains a detailed accounting of the LASPT design.

2.1.2 Light Source

A thyristor is made of silicon. In our proprietary design the light source needs to penetrate several microns into the material. To achieve this objective, the light source should be at a wavelength of 1,080 to 1,090 nm with the absorption coefficient of silicon relatively small. The ideal light source at this wavelength would be a laser diode. Unfortunately, this particular wavelength does not have applications in the market place and is not readily available. Since our budget did not include the development of 1,080 nm laser diode, we decided to use a commercial neodymium yttrium aluminum garnet (Nd:YAG) laser available in our laboratory. We used a Big Sky laser with the following characteristics:

Wavelength:	1,064 nanometers
Energy per pulse:	10 millijoules
Pulse duration:	5 nanoseconds
Pulse repetition rate:	5 pulses per second

Although the absorption coefficient at 1,064 nm is higher than at 1,080 nm, we could penetrate the thyristor to the required length because of the high energy of the Nd:YAG laser.

A production LASPT would require a diode laser at a wavelength of about 1,080 nm. Researchers have demonstrated the performance of such laser diodes. The fabrication of commercial devices, however, will require further engineering development.

2.1.3 Optical Fiber Coupling Design

The efficient coupling of the laser source to the thyristor was a major technical challenge. Obtaining the high dI/dt required the illumination of an area of about 10 cm^2 on the thyristor. To achieve this objective, we had to design a large area-coupling device with semi-uniform illumination. We treated the circumference of the optical fiber in a manner that the light leaks from its walls rather than from the small diameter (< 0.5 mm) at the end of the fiber.

We contracted with SRI International of Menlo Park, California to design and develop the optical coupling device. The initial approach was to manually abrade the walls of a glass optical fiber. This approach was not successful, mainly due to the poor uniformity of the output light distribution. We concluded that to achieve uniformity it was necessary to integrate the optical fiber with a holder and to chemically etch its wall in a controlled process. Such a technology is available at the Photera Corporation in San Diego, California. Due to budgetary and time constraints we could not transfer the Photera technique of producing leaky glass fibers to OTC. We found that leaky plastic optical fibers are manufactured by Poly-Optical based in Irvine, California. After examining the uniformity of the plastic fibers, we concluded that they were suitable for our demonstration. Appendix II provides the details of the optical fiber coupling design, showing both the output uniformity of the glass fibers and the optical fibers.

Plastic fibers cannot be used in commercial LASPT products because the absorption coefficient of 1,080 nm radiation in this material is too high. In addition, they cannot operate in a high temperature environment. For demonstration purposes, however, they were adequate. The fabrication of commercial LASPT devices requires the implementation of the etching technology of glass optical fibers as developed by Photera.

2.2 LASPT Test Station and Measurement Techniques

2.2.1 Test Equipment

Verifying the performance of the LASPT required building a low inductance, capacitive discharge circuit that could deliver the current (15 kA) and rise-time specification (<1.5 µs for a dI/dt of 10kA/µs) at a voltage of ~3000 volts (Figure 1 and

Figure 2).

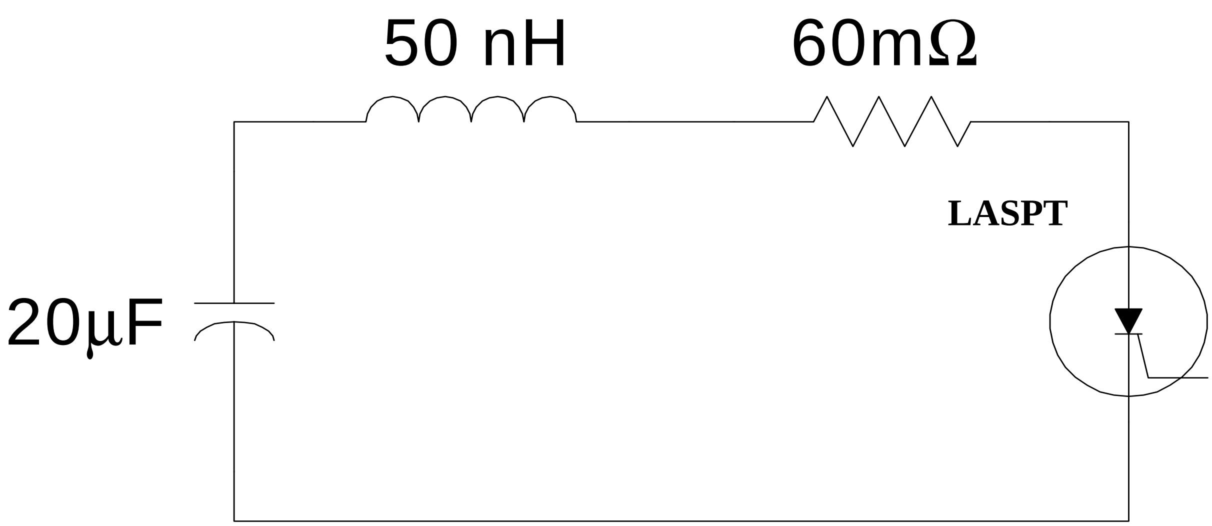

Figure 1. Schematic of the Test Station

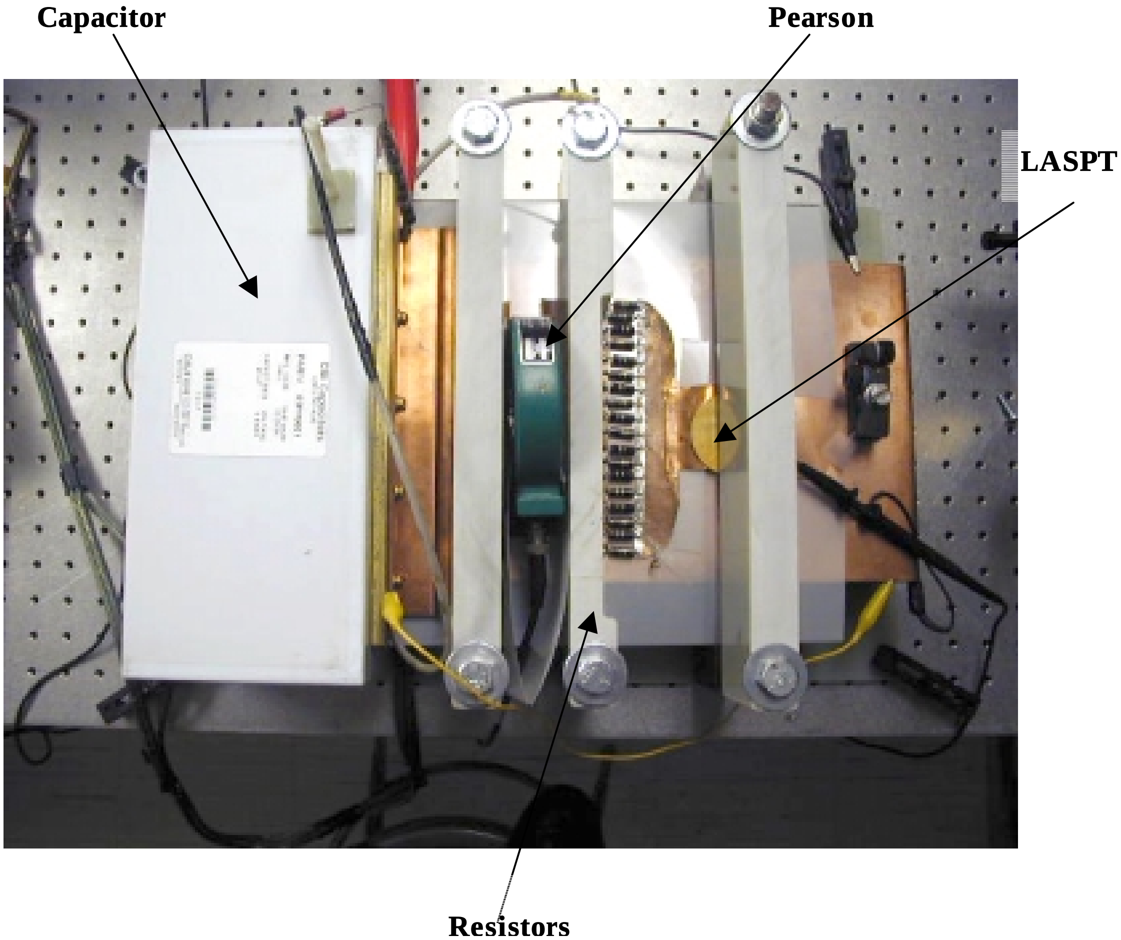

Figure 2. Photograph of the Test Station

The circuit used parallel plate bus bars for a total circuit inductance of 50 nH. At 3 kV these circuit parameters will allow a maximum dI/dt of 60-kA per µs at 3000 volts, well exceeding contract testing requirements. Appendix III contains details of the test station.

2.2.2 Test Procedures

OTC tested the LASPT in the high power test station. Circuit operation was:

- The capacitor is charged with a high voltage DC supply.
- A high voltage 1000:1 probe that plugs into a digital voltmeter monitors the charging voltage.
- At peak voltage, the laser and a Tektronix TDS224 oscilloscope is triggered. The current is measured with a Pearson Current Transformer that produces 0.05 volts per ampere. This unit is calibrated by the manufacturer and uses low inductance precision resistors whose resistance value is calibrated with National Institute of Standards and Technology (NIST) traceable standards.

- The current transformer is plugged into a Tektronix TDS224 oscilloscope in which the current waveform was displayed. The oscilloscope has an Institute of Electrical and Electronics Engineers (IEEE) port, allowing the data to be downloaded to a personal computer (PC) for further analysis. We obtained the peak current (Ipeak) by measuring the peak voltage from the oscilloscope trace and using the calibration factor. The rise-time (τ) is measured by reading it directly from the oscilloscope. Ipeak/τ gives the dI/dt rating of the switch.

Appendix III contains a detailed report of the testing procedure.

2.3 Production Readiness and Fabrication Cost

The implementation of LASPT devices in commercial systems will be accomplished only if the price of such units is competitive. We, therefore, analyzed the production readiness of LASPT devices and their fabrication cost.

We developed a Work Breakdown Structure (WBS) consisting of all the work elements required to fabricate and test an LASPT device. The five major tasks were to:

- Fabricate a thyristor
- Fabricate a cover with an optical fiber coupling device
- Fabricate a laser light source
- Integrate the LASPT device
- Test the LASPT device

We broke each major task down to its sub-tasks and then identified the critical processes, equipment, material, and manpower required to accomplish each. Appendix III contains the WBS together with the spreadsheet from which we derived the fabrication cost.

3.0 Project Outcomes

The LASPT project was very successful, both technically and economically. Technically, we were able to design the LASPT with advanced computer models that predicted the experimental behavior. More importantly, all the project goals were exceeded.

Figure 3 shows the LASPT current waveform as measured in the high power test station.

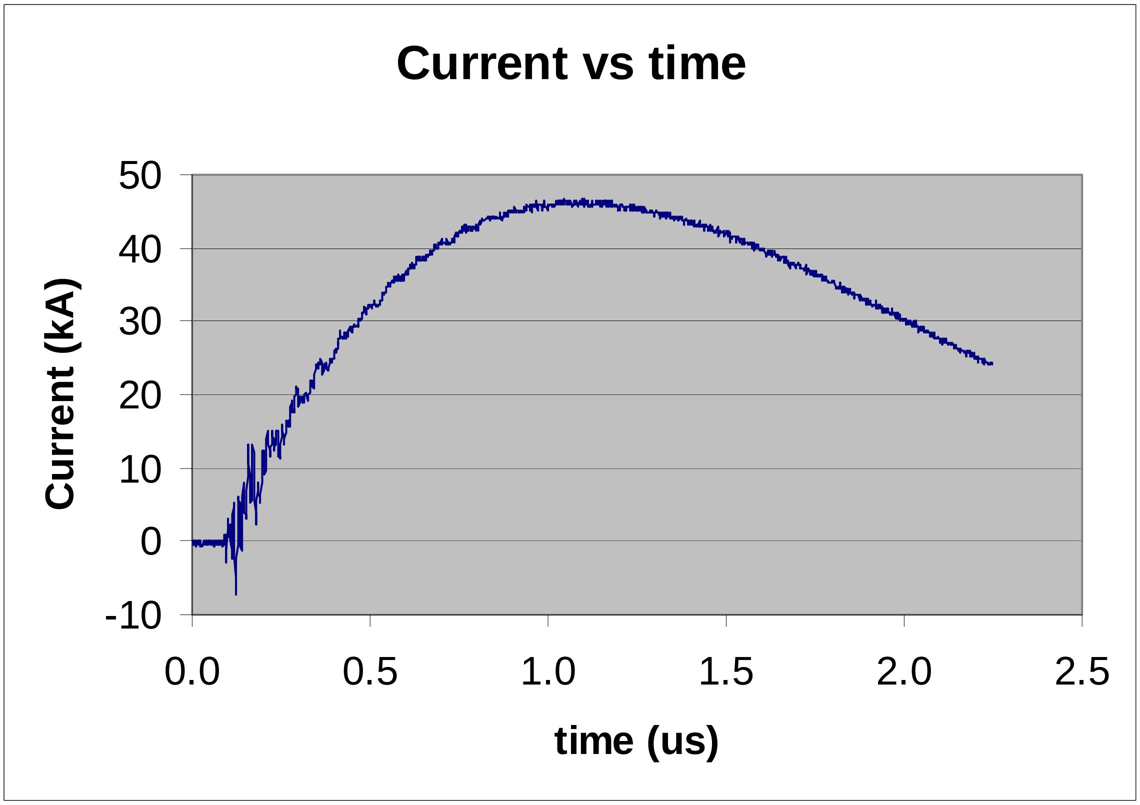

Figure 3. LASPT Current in Kilo Amperes as a Function of Time

The peak current is 47 kA and the rise-time is 0.9 µs giving a peak dI/dt of 52 kA per µs. A dI/dt of 52kA per µs is 420 percent larger than the contract goal of 10 kA/µs. Table 2 provides the test data.

Table 2. Test data from 52kA/µs experiment

Voltage (kV)	Light Energy (mJ)	Ipeak (kA)	Rise-time (µs)	dI/dt (kA/µs)
2.0	18.0	17.0	0.9	18.9
3.5	18.7	35.0	0.9	39.0
4.0	19.25	41.0	0.9	45.5
4.4	18.0	47.0	0.9	52.0

Table 3 is a comparison between the highest dI/dt test and the contract requirements. (Note: Results of further tests indicate that less than 6 mJ of energy is required to achieve these dI/dt levels).

Table 3. Project Goals and Outcome.

LASPT Parameter	Required Under Contract	Measured	Percentage Increase
Blocking Voltage	2,700 volts	4,400 volts	63%
Peak Current	15,000 amperes	47,000 amperes	213%
Rate of Rise of Current	10,000 amperes/ microsecond	52,000 amperes/ microsecond	420%

OTC also met our economic objective. We demonstrated the performance of prototype LASPT devices using standard industry techniques. The estimated production cost of LASPT devices is $700 to $1,200 per unit depending on the production volume. Given the higher performance of the LASPT, this cost is competitive with other solid-state switches.

4.0 Conclusions and Recommendations

4.1 Conclusions

Under this project OTC developed a prototype LASPT switch and demonstrated its performance. The major technical objective was to achieve a dI/dt of 10,000 amperes per microsecond, which is an order of magnitude larger than the current-based thyristor. We achieved a dI/dt of 52,000 amperes per microsecond with an increase of the voltage blockage and the current. We also concluded that such switches could be fabricated at a cost of approximately $700 for large-scale production.

The superb technical results of this research and development (R&D) project clearly demonstrate that these fast switches have the potential of protecting electric power plants and distribution centers from fast surges in power resulting from lightning or equipment malfunction. Implementation of these devices by the electric power industry would increase the reliability of the power system in California, and save billions of dollars for power producers and users.

Our major conclusions are:

- No critical technological or scientific developments are required to fabricate LASPT devices.
- The implementation of a production line of LASPT devices requires non-recurring-expenses in the following areas:
  - Production of a 1,090 nm laser diode light source
  - Implementation of a technique to chemically etch glass optical fibers
  - Development of a robust package of the LASPT device.

  OTC estimates the cost of these tasks to be $350,000.
- The fabrication cost of LASPT devices in batches of 100 units is $1,200 per unit. This cost could be reduced to approximately $700 for large volume production.

4.2 Benefits to California

The foremost achievable benefit from the proposed LASPT project is an increase in the reliability of electrical power for all California users by reducing interruption frequency and severity from severe power transients caused by lightning strikes, switching surges, power line faults, and equipment malfunctions. A secondary benefit would be a reduction in electrical rates to California users because of the reduction in damage and subsequent cost of replacement power that is passed on to the user when these faults occur.

In addition to the direct benefits of electrical reliability and cost saving, Californians stand to benefit in two other key areas: semiconductor manufacturing jobs and the development of the optical coupling technology.

First, the success of this project will lead directly to OTC's manufacturing thyristor devices and a growth in California jobs. An estimate for possible 2003 market revenues for proposed OTC's light activated thyristor products is $14 million.[6] It is predicted that this number will grow substantially over the next five years. OTC intends to protect patent rights, proprietary technology rights, and manufacturing know-how by fabricating the light activated optical coupling pieces of the commercial end product at its San Diego, California facility. We will select a commercial manufacturer to accomplish market access and the large scale manufacturing of the electrical utility devices.

Second, the technology that results from completing this project leads directly to numerous other semiconductor development projects both for OTC and the general industry. The scientific and engineering advancement in the activation of large area semiconductors with laser light will revolutionize the photoconductive switching industry and lead to new families of commercially realizable electrical utility industry products and industrial applications. Such applications include FACTS, high power UPS, static switches, synchronous rectification, traction drives, induction heating, and high voltage direct current systems.[6] These applications are initially achievable within five to ten years after project initiation with additional applications reached in the next century and beyond.

4.3 Recommendations

The next stage in this project is to demonstrate the performance of fast LASPT devices in industrial systems. We identified the following application of LASPT devices that relate to energy saving:

- Protecting electric power facilities from very fast power surges
- Controlling high power electric motors
- Providing a fast switch for an inertial fusion energy power plant that generates clean power

We are exploring the feasibility of demonstrating the performance of an LASPT based surge protection system with American Electric Power (AEP), which has several electric power plants in Ohio and other states in the Midwest. We also plan to discuss this subject with power plants owners in California and other states.

We are in touch with Rockwell International, which produces electric motors. It is our plan to demonstrate the LASPT device performance in their research facility at Thousand Oaks, California in the near future.

DOE is providing funding to the Navy Research Laboratory (NRL) in Washington, D.C. to demonstrate a inertial fusion energy power plant that can produce clean electric power at competitive cost. Titan/PSI based in San Leandro, California is under contract to the NRL to provide a pulsed power system that requires a fast switch for this project. OTC is negotiating with Titan to design and fabricate a switch based on the LASPT technology.

The LASPT device fabricated under this project was a prototype designed to demonstrate its capabilities. To implement these devices in industrial systems, it is necessary to build a robust production type unit. It is, therefore, recommended that the Commission fund additional R&D tasks that demonstrate the capability of LASPT devices to reduce energy cost in industrial systems.

The following three tasks are recommended for funding:

- Developing a low cost laser light source at 1,090 nm

- Implementing a glass etching technique to produce low cost optical coupling devices
- Developing a production type robust package for LASPT devices

A successful completion of these tasks will provide the opportunity to implement LASPT devices in electric power plants and demonstrate their capability to increase the reliability of the California electricity system while reducing the cost of electric power to California ratepayers.

5.0 Glossary

k	kilo
μ	micro
Ω	Ohm
A	ampere
AEP	American Electric Power
dI/dt	Rate of rise of current
DOE	U.S. Department of Energy
F	Farad
FACTS	Flexible AC transmission systems
H	Henry
IEEE	Institute of Electrical & Electronics Engineers
J	Joule
LASPT	Light Activated Surge Protection Thyristor
M	milli
Micron	micrometer
μm	micrometer
N	nano
Nd:YAG	neodymium yttrium aluminum garnet
Nm	nanometer
NRL	Navy Research Laboratory
NIST	National Institute of Standards and Technology
OTC	OptiSwitch Technology Corporation
PIER	Public Interest Energy Research
R&D	Research and Development
Thyristor	Switch activated by electrical current
UPS	Uninterruptible power supply
WBS	Work Breakdown Structure

6.0 References

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Appendix I

LASPT System Analysis and Design

Appendix II

Optical Fiber Coupling Design

Appendix III

Test Station and Measurement Procedures

Appendix IV

LASPT Production Readiness Analysis

Appendix I

LASPT System Analysis and Design

Appendix I : LASPT System Analysis and Design

Summary

In accordance with the statement of work for Task 2.1, OTC conducted a system study of the LASPT, using an advanced 2D simulation code. The objective was to design the optical openings in the thyristor such that the blocking voltage is reduced by no more than 10% and a dI/dt of >10kA/μs is achieved. All the simulations in this Appendix were performed using the Medici program purchased from the Avant! Corporation.

The optical opening dimension and doping profiles were varied. We consider the details of the opening configuration as a proprietary design and it is not outlined in this report. It was determined that we could design the opening such that the forward blocking is reduced by only 3.4%. When activated with 88μJ of light, the current reaches 17.9kA in 1μs giving a dI/dt of 17.9kA/μs.

1.0 System Study of Voltage Breakdown

The forward voltage breakdown study was performed using various optical opening dimensions and configurations. We have started the simulation with a standard thyristor with optical opening, and then proceeded with custom design thyristors. Dynex is the supplier for both the standard and custom devices. For the standard doping profile we used a Dynex DCR1008 thyristor (see Figure 1 for the diffusion profiles). The diffusion profile is the same for both the standard device and for the custom device. The only difference between the devices are the dimensions and the configuration of the optical openings. We consider these design as proprietary information.

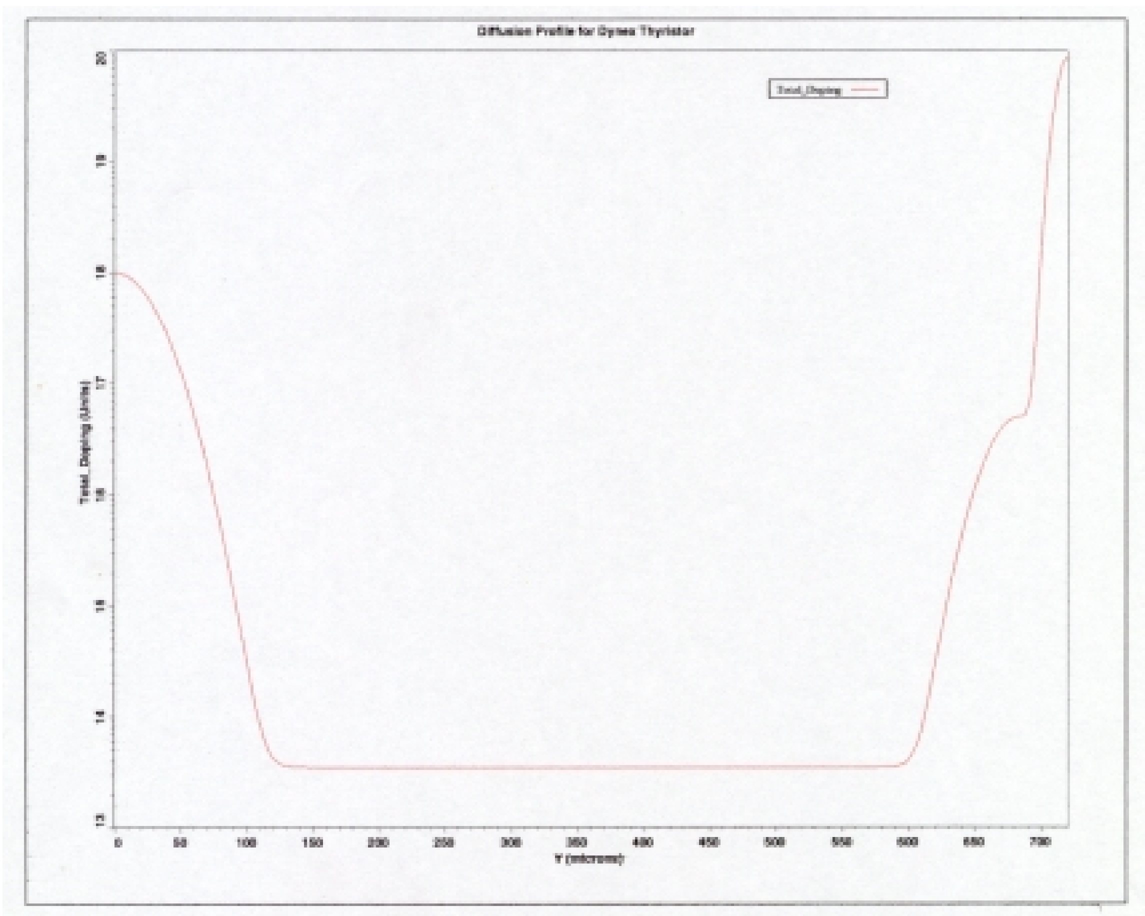

Figure 1. Diffusion profiles for the Dynex based LASPT (standard and custom).

We have started the simulation with the standard thyristor and simulated the anode current versus anode voltage for various optical opening dimensions. The results are shown in Figure 2. As shown in the figure, various optical openings can achieve the desired result of <10% reducing in blocking voltage.

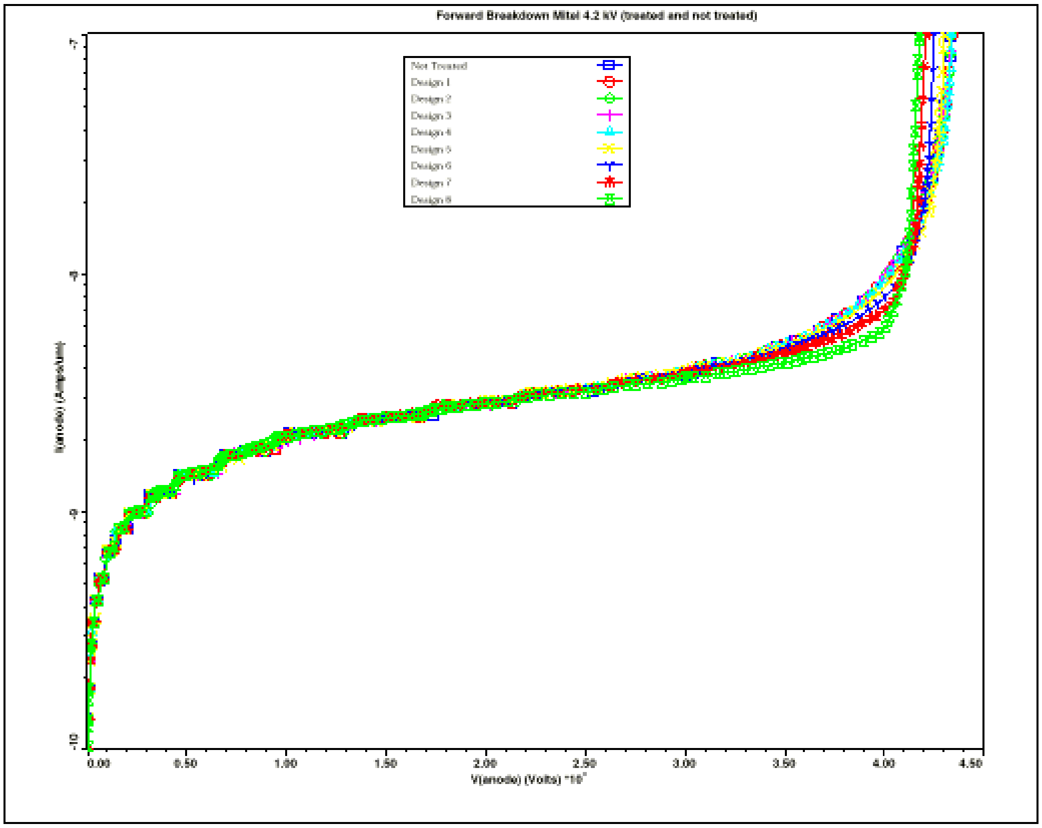

Figure 2. Plot of the anode current versus anode voltage for a standard device without and with various optical openings dimensions.

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2.0 Transient Analysis

In the transient analysis the dI/dt was determined as a function of light energy and optical opening dimensions. First, a non treated standard device was simulated to get a baseline performance. Figure 3 shows the anode current versus time for various generation rates (light energy) and three current densities. These devices were simulated in a simple RC circuit (R=10Ω, C=1mF). The carrier density created by the light pulse is calculated by multiplying the optical pulse width by the generation rate. The carrier density was varied from $1.5{\cdot}10^{13}$ cm^{-3} (30ns times $5{\cdot}10^{20}$) to $1.5{\cdot}10^{16}$ cm^{-3} (30ns times $5{\cdot}10^{23}$). As shown in the plot, to reach the peak current density in 1 μs the switch requires an initial carrier density of $1.5{\cdot}10^{15}$ cm^{-3}. This corresponds to 400μJ of light for a total area of $20cm^2$, and a total device thickness of 720μm.

Next, the device was simulated in a more realistic test circuit to verify the dI/dt performance (C=4μF, R= 15mΩ and L=75nH). Figure 4 shows a plot of the current versus time for an initial carrier density of $15{\cdot}10^{15}$ cm^{-3}. The current reaches a peak value of 17kA in 1.1μs for a dI/dt of 15.4kA/μs well exceeding the goal of 10kA/μs.

The transient response of a device with an optical opening was simulated using the ray tracing routine of the 2D simulation program and with the full light absorption models. The ray tracing calculation takes into account the variation in the carrier density created by the light. The optical opening pattern allows for the activation of 54% of the total $20cm^2$ device area. Figure 5 shows the anode current versus time with an incident light energy of 88μJ. Due to the non-uniform illumination, the current flow is non uniform with a bulk of the current being carried near the optical opening where the carrier density is highest. However, this high carrier density reduces the on-state drop, so peak current is slightly higher. As shown in the figure, a peak current of 17.9kA is reached in 1μs giving a dI/dt of 17.9kA/μs. Thus even though the current flow is non uniform, the dI/dt goal can be achieved.

Non uniform current flow is a potential problem if the local temperature rise exceeds ~100 degrees C. The temperature was calculated using the 2D simulation program and the results indicate that the highest temperature rise is 13 degrees C, located under the optical opening. This temperature rise is well within the limit of silicon devices.

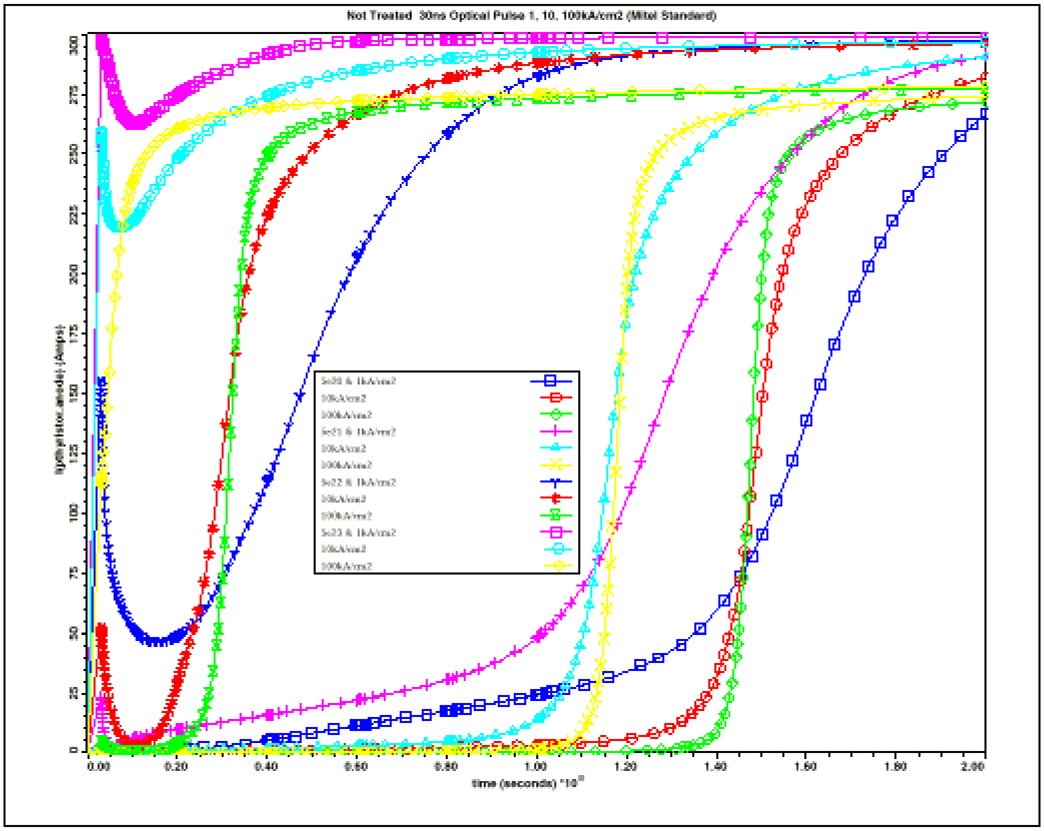

Figure 3. Anode current versus time for a non-treated device with various current densities and initial light energies.

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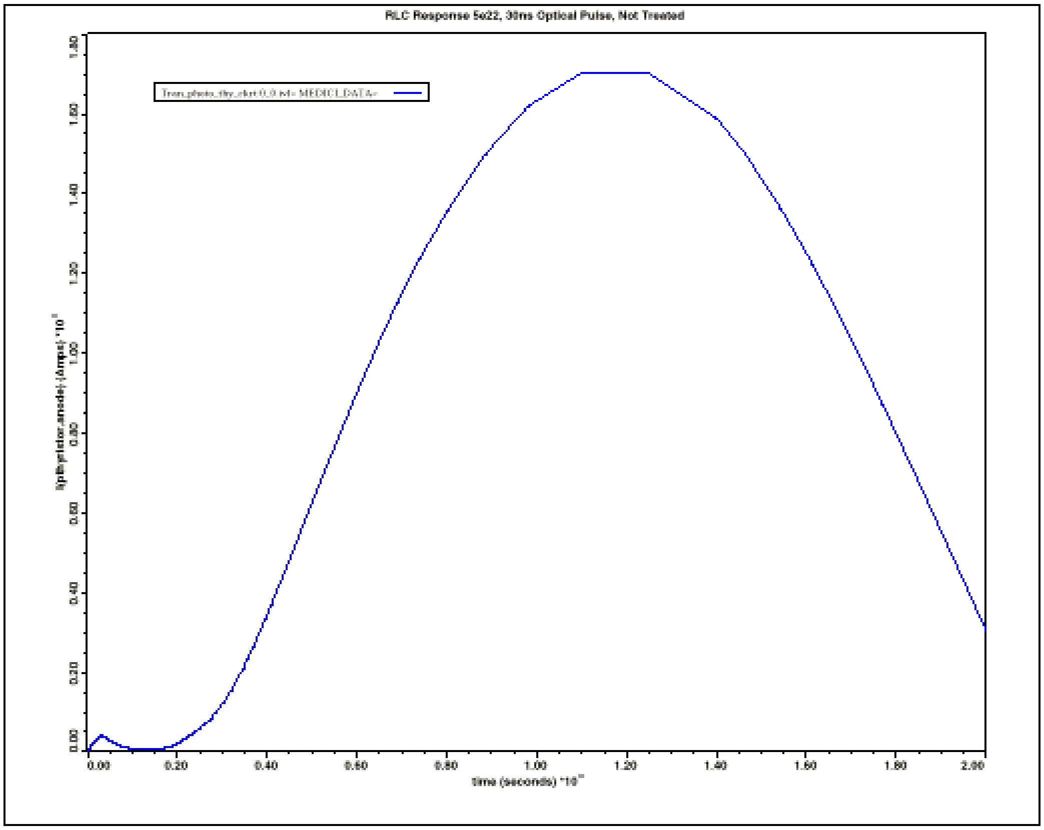

Figure 4. Plot of the anode current versus time for an initial carrier density of $1.5 \cdot 10^{13}$ cm^{-3}. The current reaches a peak value of 17kA in 1.1μs for a dI/dt of 15.4kA/μs.

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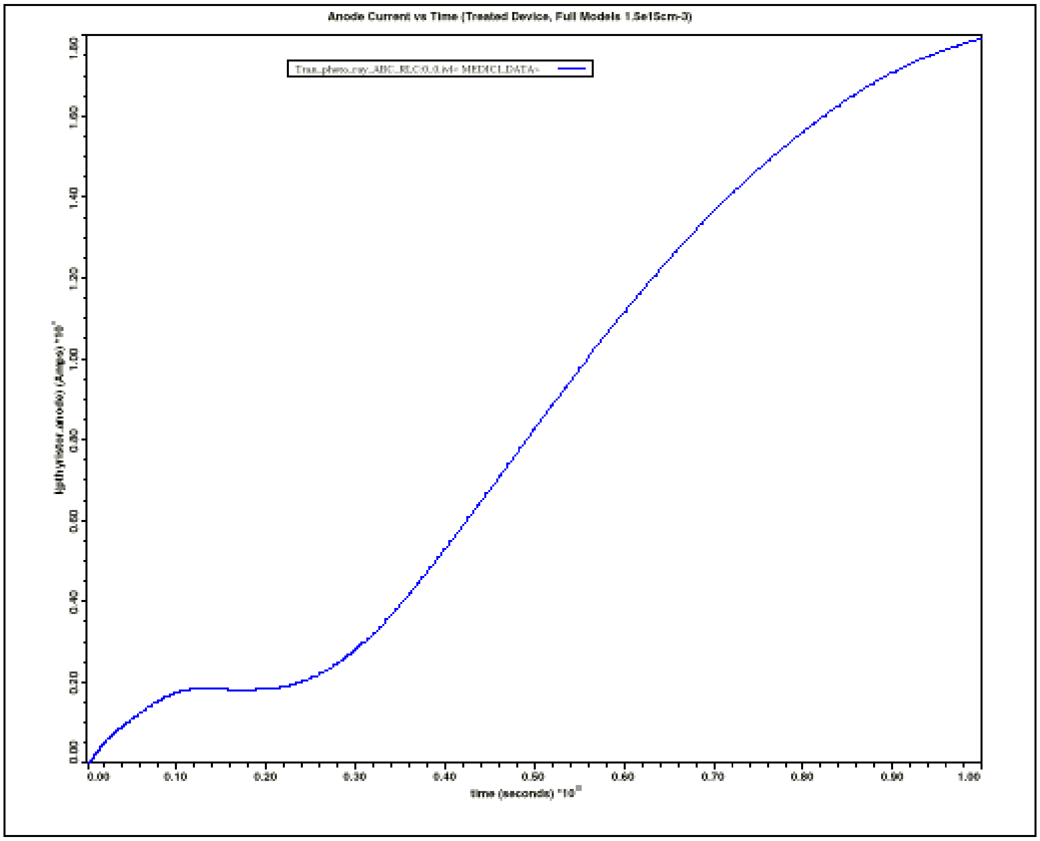

Figure 5. Anode current versus time for the treated LASPT. The peak current is 17.9kA in 1µs for a dI/dt of 17.9kA/µs.

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3.0 Conclusion

In conclusion, the LASPT will be constructed with an optical opening with a calculated breakdown voltage of 4.2kV compared to 4.35kV for a non-treated device. This is a reduction of only 3.4%. By employing a rectangular array of 16, openings, spaced 2mm apart, 54% of the total area can be activated. If 88μJ of light is incident on all the openings a dI/dt of 17.9kA/μs is achieved.

Appendix II

Optical Fiber Coupling Design

Appendix II: Optical Fiber Coupling Design

Summary:

The objective of this task was to design an optical fiber that leaks from the walls rather than from the end of the fiber. The design of the leaky fiber with its holder was performed by SRI International of Palo Alto, California. SRI developed a technique to manually abraid the walls of glass optical fibers. This approach did not produce the uniformity distribution of the leaked radiation that is required for this project. Leaky plastic fibers, that are available commercially, were used for this project. Although the plastic fibers provided the required uniformity, they are not suitable for industrial applications. For commercial products it will be necessary to implement a technique to chemically etch glass fibers.

1.0 Introduction

The purpose of this task was to design an optical fiber coupling system that will efficiently generate sufficient electrons and holes in the thyristor, to obtain the high dI/dt required for this program. The general approach was to design fibers that leak from the walls, rather than from the end, and a circular "puck" with the leaky fibers embedded in slots. A critical issue in this approach was the output uniformity of the leaky fiber. This task was mainly performed by SRI.

The first experiments were done with a standard silica (glass) fiber, stripped of its cladding layers and abraded manually. In this method, the radiation leaked out in an exponential manner from the entrance of the laser source to the abraded fiber. This output distribution was not adequate for our program.

The next approach was to use leaky plastic fibers manufactured by Poly-Optical in Irvine, California. The output radiation uniformity of these fibers is sufficient for the current program. The disadvantage of plastic fibers is the high transmission loss of 1064nm radiation, the low operating temperature and the low optical damage threshold. Therefore, we have investigated an etching technology for glass fibers, developed by Photera in San Diego, California. Following detailed discussions with Photera, we have concluded that their technology will provide the required output uniformity of leaky glass fibers. Transferring the Photera technology to OTC at this time would have delayed the schedule of the current program. Thus, OTC has decided to use plastic fibers for the current program and to license the etching technology from Photera in the future.

2.0 Preliminary Studies of Abraded Glass fibers

In order to provide a proof of concept demonstration for the optical activation of a thyristor using 1060 nm light, experiments were undertaken to demonstrate the activation of a LASS bar, using mounted optical fibers treated to provide more-or-less uniform light leakage along their length. A number of copper bars, 5 cm long, 4 mm wide and 1 mm deep were machined with 2 parallel slots, (each 500 micron wide, 250 micron deep) 2 mm apart, along the long axis of the bar (see Figure 1; image quality is poor due to the difficulty of photographing a reflective object). An optical fiber was glued into the slots using epoxy cement. The composition of the fiber was:

Silica core (refractive index 1.457); diameter – 200 micron
TECS clad (refractive index 1.404); core + clad diameter – 225 micron
Tefzel buffer (refractive index 1.403); total diameter – 500 micron.

TECS is a proprietary material produced by 3M; Tefzel is a fluorinated polymer similar to PTFE produced by DuPont. This fiber was used for all the tests described in this report.

The buffer was removed from the exposed portion of the fiber in the slot with a razor blade; a 4 cm long portion of the exposed cladding was then abraded with fine SiC paper. The fiber not in contact with the copper bar was not treated, thereby retaining its flexibility. (Although only one fiber is required for LASS bar activation, two slots were cut in each bar in order to determine whether a single, looped fiber could be mounted in both of them, thereby eliminating the wastage of light from the fiber ends. The desirability of this approach is still under discussion). The photograph below shows the finished bar.

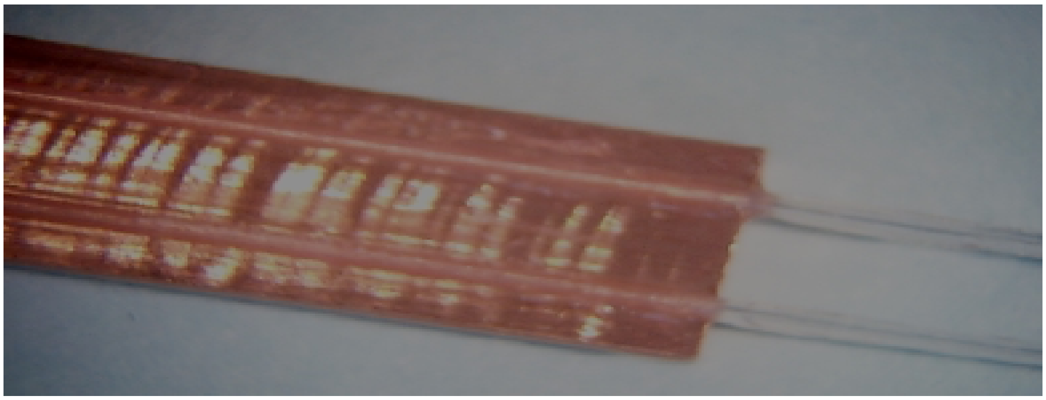

Figure 1. A photograph of a copper plate with two slots and an embedded fiber

Using the red light from a He-Ne laser (10 mW input power), the extent and uniformity of light leakage from the abraded portion was determined photographically. The photograph in Figure 2 shows an example of the leakage behavior from a single fiber (with light input from the left-hand side; the bar under the photograph indicates the 4 cm abraded portion). While it is apparent that some leakage occurred from unabraded parts of the fiber, it is believed that this can be minimized by careful handling. The uniformity of leakage in these preliminary tests was considered encouraging.

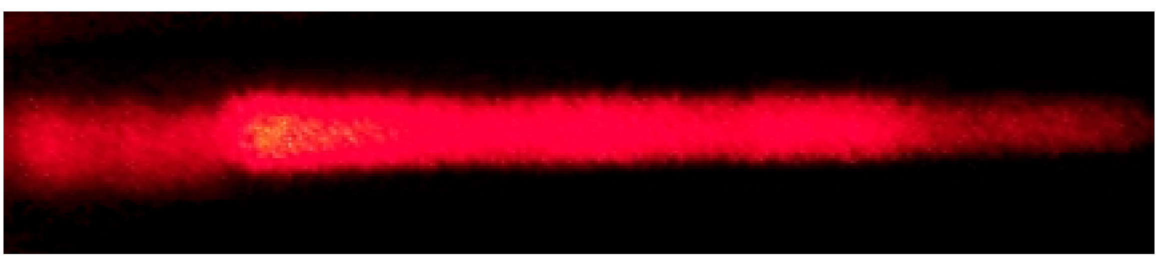

Figure 2. A photograph of the light leakage from an abraded fiber.

In order to determine quantitatively the uniformity of light output from a mounted fiber, a number of fibers were mounted in copper bars, as described above, and selectively abraded in certain regions. The uniformity of light leakage was determined by placing a calibrated photodiode (circular, 0.8 cm in diameter) at selected lengths along the fiber. The fiber was illuminated with red light from a He-Ne laser. A variety of abrasion patterns were tested. The light emission results of two partially abraded fibers are shown in Figure 3 (series 3 and 4), with those for two fully abraded fibers (series 1 and 2) for comparison. The abrasion pattern giving the best results involved alternating bands (about 0.5 cm long) of abraded and unabraded regions over the first half of the fiber, with complete abrasion over the second half. In the chart below, the fraction of the total light emitted is shown as a function of distance from the light entry point. As is apparent, in the best case to-date, an intensity variation of about 10% along the length of the fiber has been obtained.

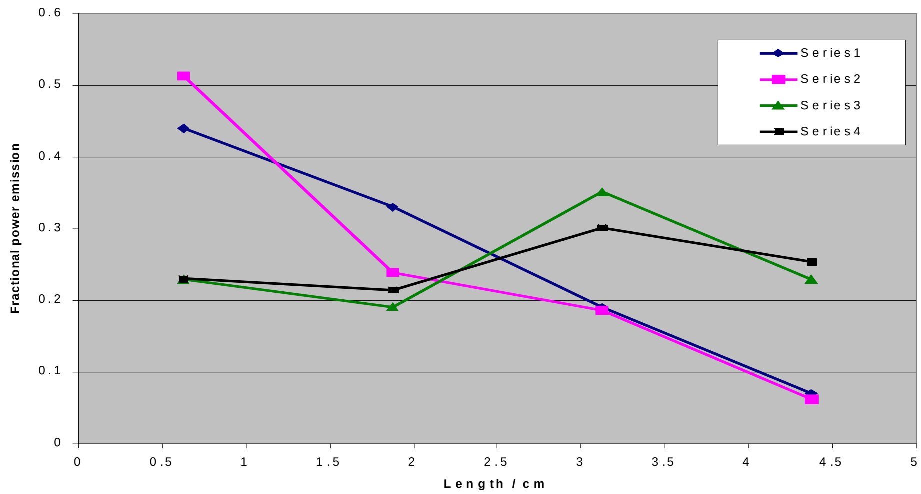

Figure 3. Output power from partially and fully abraded fibers

In addition to some variability from sample to sample, with nominally the same abrasion pattern, variability was encountered with respect to the angle of initial light entry into the fiber. This is to be expected since the entry angle impacts the amount of light which passes straight through the fiber, i.e. the fraction of light modes within the fiber whose rays do not intersect the fiber surface and which cannot leak out. This provides another means of controlling the emission profile.

3.0 Manufacture and testing of a prototype large-area illuminator

Following the manufacture and testing of mounted fibers, the assembly of a prototype of a complete illumination unit was undertaken. A copper plate was prepared (the "hockey puck") with a series of 250 micron deep, 500 micron wide slots. These slots are spaced to correspond to the optical openings in the LASPT.

Manual removal of the buffer, followed by abrasion of each fiber, produced variable light-leakage performance from fiber to fiber. This observation is in accord with previous results concerning light leakage behavior – although manual treatment of the fibers can give excellent results, the degree of control and reproducibility is not high. This subject will be dealt with separately below.

Once sufficient experience with fiber abraison, as it determines the uniformity of light leakage, was accumulated, it was decided to determine if a *single*, continuous optical fiber can be used, in conjunction with the hockey puck described above, to produce a more-or-less uniform field of illumination. Should this be the case, the use of a single fiber would simplify considerably the manner of light input to the illuminator, versus the case in which a plurality of independent fibers were employed. To this end, approximately 20 ft of buffered fiber was glued into eighteen of the slots in the copper plate, as shown in the accompanying photograph, and abraided. The two fiber ends were attached to a single light source at 800 nm and the illumination pattern was photographed, as shown in Figure 4. The result was very encouraging, revealing an encouragingly uniform pattern of illumination.

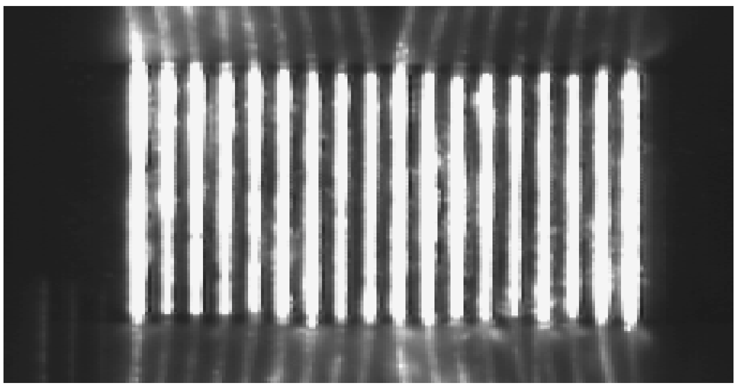

Figure 4. A copper plate with a single fiber folded and embedded in 18 slots.

In order to quantify this result better, the relative intensity distribution was determined with a CCD camera. The result is shown Figure 5 (in this image, the plate is rotated

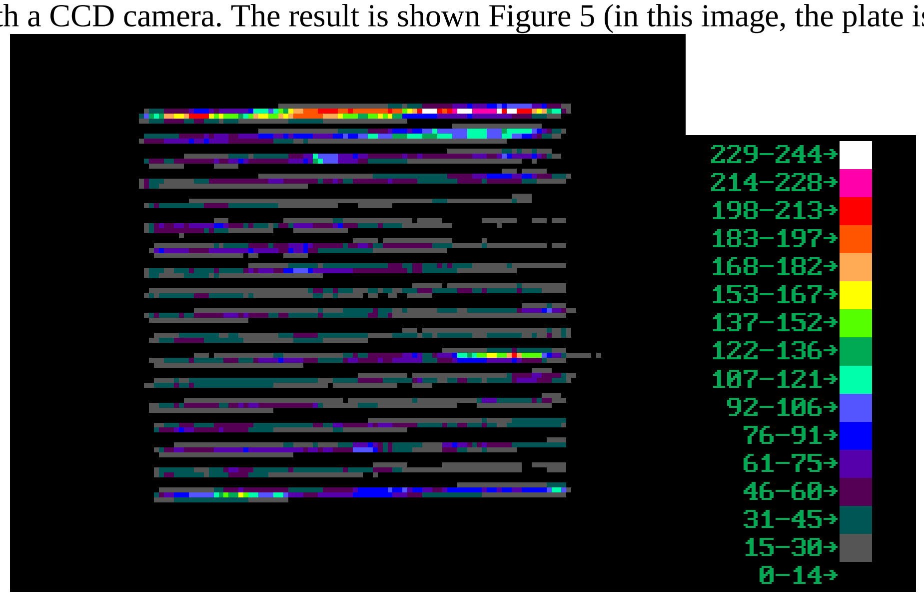

Figure 5. A picture of an illuminated single fiber embedded in 18 slots

through 90° relative to the image shown above), with the corresponding *linear* intensity scale (which is divided into sixteen equal, color-coded, elements). The camera aperture was adjusted such that saturation was avoided at all locations. Since one fiber (at the top of the picture) showed more intense emission than the others, most of the remaining intensity signal is displaced towards the bottom of the intensity scale; nonetheless, the emission is again seen to be more-or-less uniform, if this rogue fiber element is excluded. Although this particular element is closest to one of the light inputs, it should be noted carefully that the other input (at the bottom of the figure) is not so extremely different, and yet the input light powers were the same. Again we see that great care is required when processing this system by hand. The actual system described here was delivered to Optiswitch for further optical characterization.

OTC has developed a more accurate point measurement instrument for testing leaky fibers. Both the single fiber, as well as the large area fiber embedded in 18 slots, were tested. The results of a single fiber is shown in Figures 6. It is obvious that most of the radiation is leaked out from a small portion of the fiber near the laser input, and it decays in an exponential form. This output distribution is not adequate for the current program.

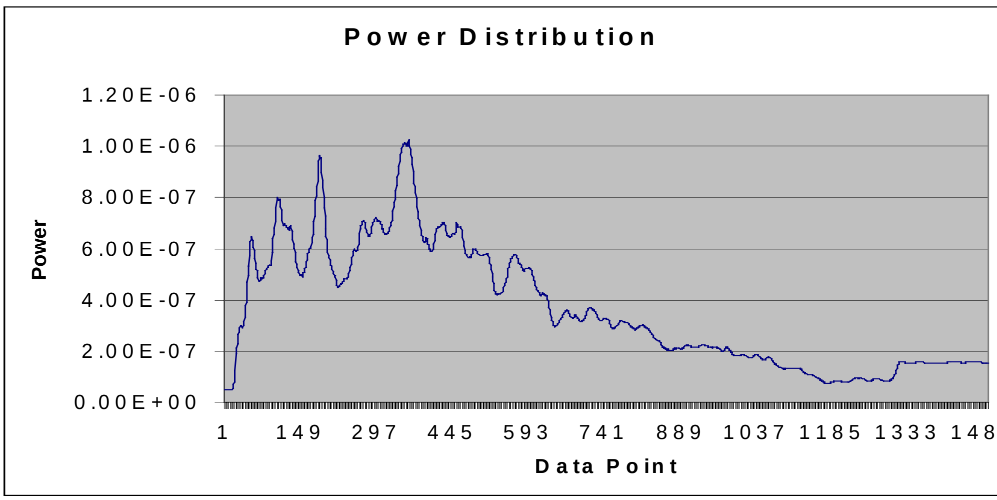

Figure 6. Power output of a leaky glass fiber

4. Alternative methods for achieving fiber leakage

Although manual treatment of fibers may eventually give acceptable leakage results, it is not a process suited to mass production. Accordingly, alternative methods for fiber treatment are being sought by Optiswitch. These involve chemical etching of the fibers and the use of pre-made, notched plastic fibers. The compatibility of the copper used to make the hockey puck with the chemicals required for the etching approach is under investigation. Copper fiber holders (with slots 250 microns wide and deep) for the plastic fibers have been made and sent to Optiswitch.

Plastic leaky fibers are readily available from Poly-Optical, Irvine, California. We have tested such a fiber and the power distribution is shown in Figure 7. The power distribution uniformity of plastic fibers was adequate for our program, and they were used in the fabrication of the prototype LASPT devices. Production type LASPT devices will require glass leaky fibers. The Photera Corporation of San Diego developed a chemical etching technology to produce glasss leaky fibers. OTC is considering licensing the etching technology from Photera.

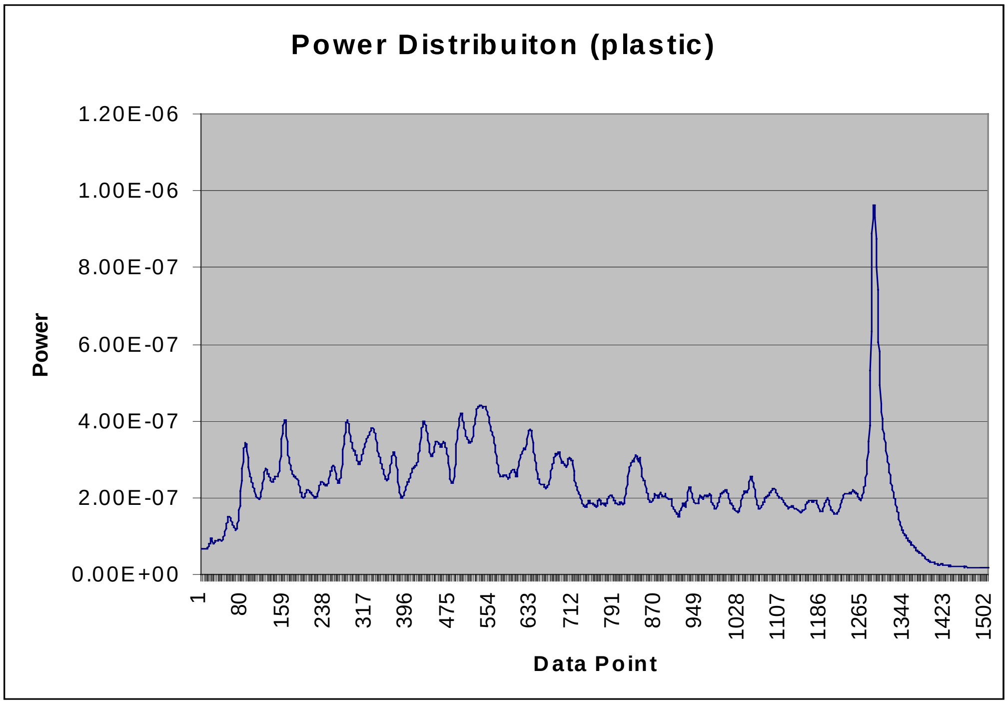

Figure 7. Power output of a leaky plastic fiber

Appendix III

Test Station and Measurement Procedures

Appendix III: Test Station and Measurement Procedures

Summary

This Appendix provides details of the test station that was assembled to measure the characteristics of LASPT devices and the test procedures

1.0 Introduction

The Test Plan consists of three parts:

(1) A low power test plan for LASS bars.
(2) A verification of a high power test plan using an LASPT with a standard thyristor.
(3) A test plan for an LASPT with a custom thyristor.

2.0 Testing of LASS Bars

The first test to be performed will be the testing of the LASS Bars. The quantities to be measured are:

LASS Current as a function of time
LASS Voltage as a function of time
Incident Light Energy

Figure 1 shows the circuit schematic in which the LASS Bars will be tested and Figure 2 shows the optical arrangement. These tests are necessary to determine the rate of rise of current (dI/dt) as a function of the total light energy. Simulations show that a dI/dt of 10kA/μs will be achieved with 10μJ/cm^2 of light energy incident on the device. These devices are 4cm x 2mm giving a total area of 0.8cm^2. Thus 8μJ of incident light energy is required. Taking a coupling efficiency of 70% and a fiber output efficiency of 90% (measured quantities) gives a total required energy of 13μJ.

Technical Approach

To assure the quality of the LASS before it is tested, OTC will measure the leakage current as a function of voltage. This will give a baseline performance. Once all tests are performed the leakage current will be again measured. If a substantial increase is noted, this will indicate damage, which may not be visible.

To trigger the LASS bars for transient testing OTC's Q-switched laser will be used as the activating source. Using a 50% beam splitter and a Laser Precision Pulsed Energy Meter (Model RJ-7620) the laser energy per pulse will be measured. A direct reading from the front panel LCD screen will indicate the incident laser energy.

A Tektronix 100Mhz digital oscilloscope (TDS-224) will measure all the electrical data. The TDS 224 is interfaced with a PC for data storage and analysis. The TDS is calibrated by the rental agency before shipment. To measure the current and the voltage a Pearson Probe and a Tektronix High Voltage Probe will be used. For quality assurance, the Pearson probe was calibrated by the manufacturer and the high voltage probe will be calibrated with a known voltage source.

To obtain a more accurate reading of the voltage at peak current the circuit to the right of the LASS in Figure 1 will be used. First, the IV characteristics of the diode will be measured. From this data we will know the voltage across the diode as a function of current. Next by measuring the voltage at the anode of the diode (V_A) and the capacitor voltage ($V_{Capacitor}$) we can calculate the voltage on the LASS by:

$$I_{Diode} = (V_A - V_{Capacitor})/R$$
$$V_{Diode} = F(I_{Diode}) \text{ Taken from IV data}$$
$$V_{Lass} = V_A + V_{Diode}$$

Once the diagnostic equipment is calibrated we will then begin gathering data. Two runs will be done one at 1000volts and the other at 3000volts. At each voltage level the peak current, the current rise-time (10-90%) and the voltage on the switch will be measured as a function of time and the light energy. A variable attenuator (see Figure 2) will be used to vary the light energy. Table 1a and 1b will be utilized to record the data. Once the data is gathered, the dI/dt will be calculated by dividing the peak current by the rise-time. Two graphs will be generated by plotting column 4 (dI/dt) and column 5 (Von) versus column 1 (light energy). This will be done for 1000 and 3000volts. The plot of dI/dt versus light energy will determine how much light is required to achieve a given dI/dt. We will also plot the electrical energy lost during switching ($\int I(t)V(t)dt$), column 5 as a function of the light energy (W_{dis}). This will determine how efficient the device is at switching high currents.

After the series of tests the devices will be inspected for damage. The leakage current will be measured to see if an increase occurred. This would a sign of damage that may not be visible under inspection.

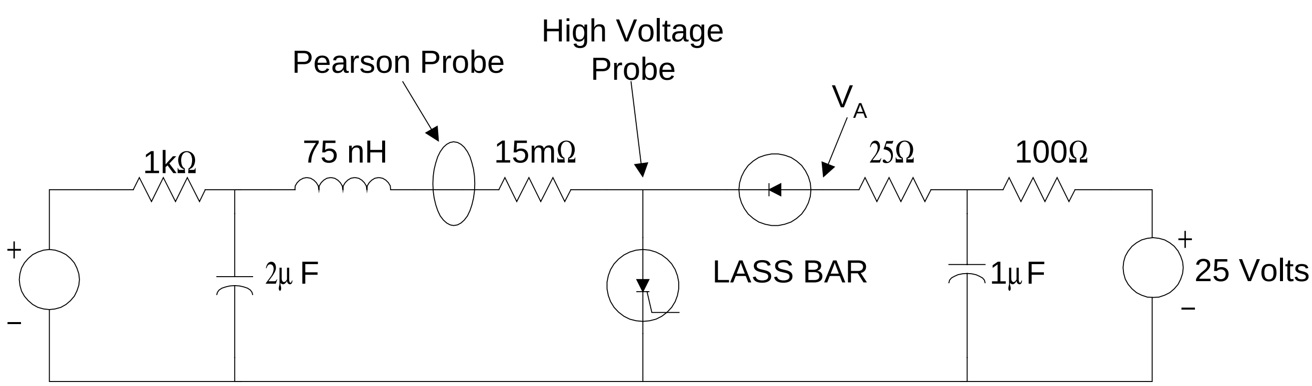

Figure 1. Schematic of low power test station.

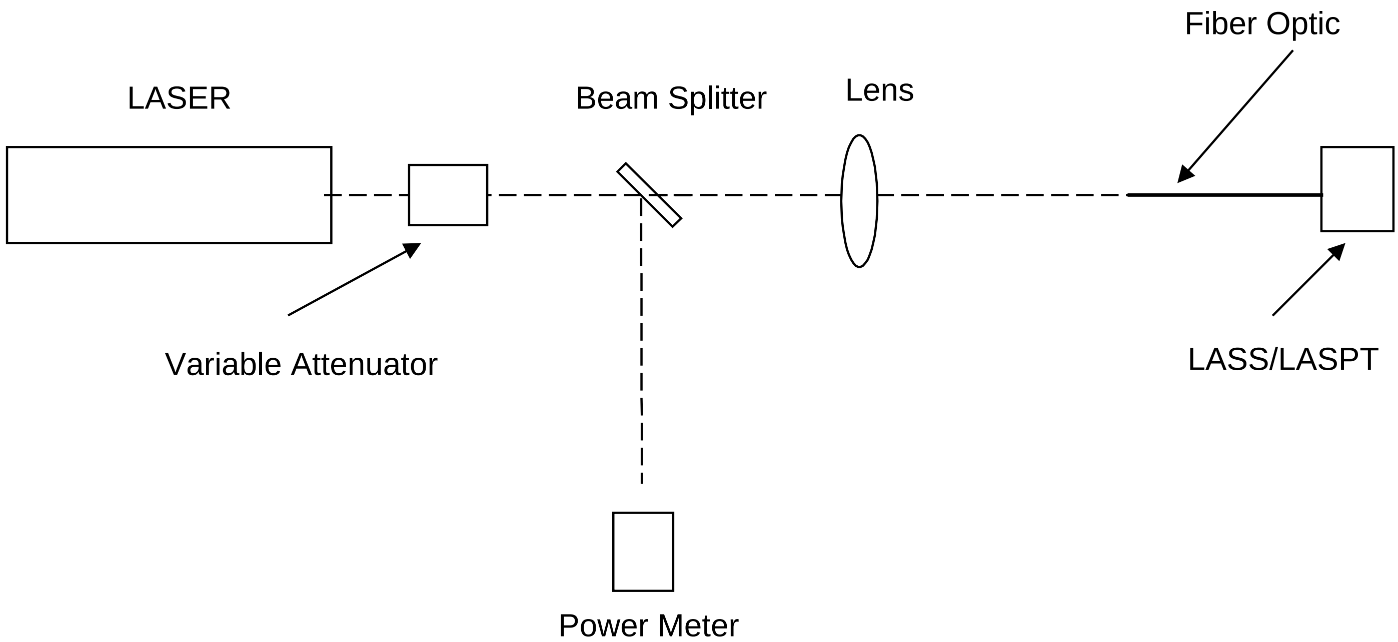

Figure 2. Optical setup to measure light efficiency.

Table 1a

Voltage=1000v

Light Energy (μJ)	Peak Current (kA)	Rise-time (μs)	dI/dt (kA/μs)	Von (Volts)	Wdis (mJ)

Table 1b

Voltage=3000v

Light Energy (μJ)	Peak Current (kA)	Rise-time (μs)	dI/dt (kA/μs)	Von (Volts)	Wdis (mJ)

3.0 Verifying Performance of High Power Test Station

To fully test the potential of the LASPT a higher power test station is required. However, before testing the Custom LASPT, the performance of the high power test station needs to be verified.

Figure 3 is a schematic of the high power test station. Like the low power test station it is also an RLC circuit, but unlike the low power test station it is capable of over 30kA at a charge voltage of 3kV. For quality assurance we need to calibrate the high voltage probe and the Rogowski Loop. The probe will be calibrated with a known voltage source and the Pearson probe will be used to calibrate the Rogowski Loop. Once calibrated, it is necessary to determine the circuit inductance and resistance (the capacitor value is known from the manufacture). To determine these values we will use either a metal to metal switch or a LASS bar to discharge the capacitor. This will be done at low voltage (500volts) and by measuring the current waveform with the Rogowski Loop the inductance and resistance can be deduced.

After measuring the circuit parameters OTC will begin testing the standard LASPT. With the standard device, the simulations showed that the device could only hold 2kV. Thus the peak current will be limited to 20 kA. However, since the standard and the custom are physically identical, testing of the standard LASPT will aid in the development of the jigs and mounting procedures which are required for testing the custom LASPT.

When testing the standard LASPT the data will be recorded in Table 2a and 2b. The tests will be run at 1000 and 2000 volts. During each shot the peak current, rise-time, and the voltage on the switch will be measured as a function of light energy. This data will be recorded in the tables. As with the testing of the LASS bars, the same diagnostic equipment will be used. From the data in Table 2a and 2b we will be able to determine the peak performance of the high power test station in terms of dI/dt rating as a function of voltage.

It should be noted that since the standard LASPT device will be inferior to the custom LASPT, these tests are primarily concerned with discovering any problems in the electrical and mechanical performance of the high power test station.

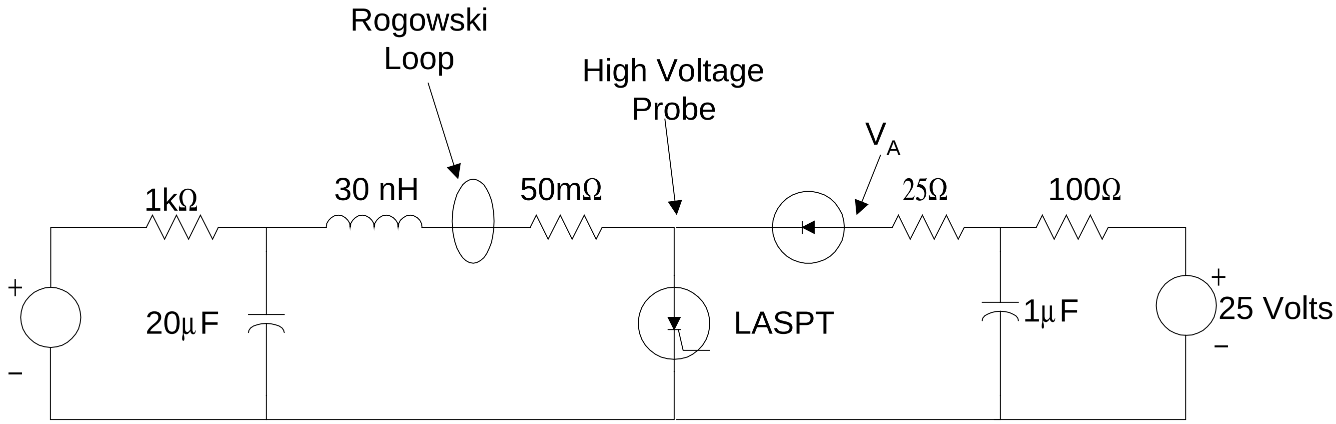

Figure 3. Schematic of high power test station.

Table 2a

Voltage=1000v

Light Energy (µJ)	Peak Current (kA)	Rise-time (µs)	dI/dt (kA/µs)	Von (Volts)	Wdis (mJ)

Table 2b

Voltage=2000v

Light Energy (µJ)	Peak Current (kA)	Rise-time (µs)	dI/dt (kA/µs)	Von (Volts)	Wdis (mJ)

4.0 Test Performance of Custom LASPT

This is the final test in a series of three tests. During this testing OTC will determine the full potential (dI/dt) of the custom LASPT (up to the limit of our test facility). The quantities to be measured are:

LASPT Current as a function of time
LASPT Voltage as a function of time
Incident Light Energy

Figure 3 shows the circuit schematic of the high power test station in which the custom LASPT will be tested and Figure 2 shows the optical arrangement. These tests are necessary to determine the rate of rise of current (dI/dt) as a function of the incident light energy. Simulations show that a dI/dt of 30kA/µs will be achieved with 91µJ of light energy. Taking a coupling efficiency of 70% and a fiber output efficiency of 90% (measured quantities) gives a total required light energy of 145µJ.

Technical Approach

To assure the quality of the LASS before it is tested, OTC will measure the leakage current as a function of voltage. This will give a baseline performance. Once all tests are performed the leakage current will be again measured. If a substantial increase is noted, this will indicate damage, which may not be visible.

To trigger the LASPT for transient testing OTC's Q-switched laser will be used as the activating source. Using a 50% beam splitter and a Laser Precision Pulsed Energy Meter (Model RJ-7620) the laser energy per pulse will be measured. A direct reading from the front panel LCD screen will indicate the incident laser energy.

A Tektronix 100Mhz digital oscilloscope (TDS-224) will measure all the electrical data. The TDS 224 is interfaced with a PC for data storage and analysis. The TDS is calibrated by the rental agency before shipment. To measure the current and the voltage a Pearson Probe and a Tektronix High Voltage Probe will be used. The Pearson probe is calibrated by the manufacturer and the high voltage probe will be calibrated with a known voltage source

To obtain a more accurate reading of the voltage at peak current the circuit to the right of the LASS in Figure 1 will be used. First, the IV characteristics of the diode will be measured. From this data we will know the voltage across the diode as a function of current. Next by measuring the voltage at the anode of the diode (V_A) and the capacitor voltage ($V_{Capacitor}$) we can calculate the voltage on the LASPT by:

$$I_{Diode} = (V_A - V_{Capacitor})/R$$
$$V_{Diode} = F(I_{Diode}) \text{ Taken from IV data}$$
$$V_{Laspt} = V_A + V_{Diode}$$

Once the diagnostic equipment is calibrated we will then begin gathering data. Two runs will be done one at 1000volts and the other at 3000volts. At each voltage level the peak current, the current rise-time (10-90%) and the voltage on the switch will be measured as a function of time and the light energy. A variable attenuator (see Figure 2) will be used to vary the light energy. Table 3a and 3b will be utilized to record the data. Once the data is gathered, the dI/dt will be calculated by dividing the peak current by the rise-time. Two graphs will be generated by plotting column 4 (dI/dt) and column 5 (Von) versus column 1 (light energy). This will be done for 1000 and 3000volts. The plot of dI/dt versus light energy will determine how much light is required to achieve a given dI/dt. We will also plot the electrical energy lost during switching ($\int I(t)V(t)dt$) as a function of the light energy (W_{dis}). This will determine how efficient the device is at switching high currents.

After the series of tests the devices will be inspected for damage. The leakage current will be measured to see if an increase occurred. This would a sign of damage that may not be visible under inspection.

Table 3a

Voltage=1000v

Light Energy (μJ)	Peak Current (kA)	Rise-time (μs)	dI/dt (kA/μs)	Von (Volts)	Wdis (mJ)

Table 3b

Voltage=3000v

Light Energy (μJ)	Peak Current (kA)	Rise-time (μs)	dI/dt (kA/μs)	Von (Volts)	Wdis (mJ)

Appendix IV

LASPT Production Readiness Analysis

Appendix IV : LASPT Production Readiness Analysis

Summary

In this Appendix we have evaluated the maturity of the technologies that are required to fabricate LASPT devices for industrial applications, and the production cost at moderate volume quantities. We have concluded that all the basic technologies for LASPT production are available. To implement a production line of LASPT devices, however, non recurring engineering expenses will be required in three areas: (1) a laser diode light source, (2) etching glass fibers, and (3) a robust industrial LASPT package. After the implementation of the improvements in these three areas, the production cost of LASPT devices will be in the range of $ 700-1200 per unit, pending on the production volume.

1.0 Introduction

An LASPT consists of three sub-systems that must be integrated into one package and tested for performance and reliability. The three sub-systems are:

I The switch, which consists of a custom made thyristor with openings for optical coupling.

II The cover and Switch, which is a “hockey puck” shape metal with leaky fibers to match the openings in the switch.

III The laser, which is a laser diode, or a solid state laser, to be connected to the leaky fiber.

These three sub-systems are fabricated separately, tested for mechanical integrity and performance, and then integrated into a robust LASPT package and tested for integrity and performance.

In the remainder of this report we will describe the different processes steps, develop a Work Breakdown Structure (WBS) for fabricating LASPT devices, and provide an estimate for fabrication cost for small volume production.

2.0 Fabrication Processes Description

2.1 Switch

The switch consists of a custom made thyristor, with openings for illumination. The current supplier for custom-made thyristors is Dynex Corporation of Great Britain. The price for an order of a lot of 100 units is $250/thyristor. For large scale production, more companies will be interested in bidding, and the price per unit might go down to approximately $ 150.

Currently Corwil of Fermont, CA is making the openings in the thyristor. For an order of 100 units, the price is $40/thyristor. This price includes changing a $500 part after 500 thyristors are processed. For large-scale production, we plan to qualify another vendor for this process, and we estimate that the price will go down to $20/thyristor.

Next the thyristors have to be cleaned, etched, and passivated to avoid oxidation of the openings. This process is done currently at OTC. It is estimated that it will take 24 man-hours to process a lot of 100 thyristors. Following these steps the thyristor will be tested for voltage holding.

2.2 “Puck” Shape Cover

The cover consists of a 2 inch diameter copper plate with slots for the fibers. The fabrication cost of the cover is $50/unit. Glass fibers are imbedded in the slots, and the cladding is etched to provide a leaky fiber. Following the etching the transmission properties and the intensity distribution of the leaky fiber are tested.

2.3 Laser Source

In general the laser source can be either a laser diode or a solid state laser, pending on the application. To obtain the technical objectives outlined in this project a laser diode emitting radiation at 1.1μm is required. Laser diodes at this wavelength are not readily available, since there are not many applications for this particular wavelength. The technologies that are required for fabricating these devices are similar to those of other wavelengths and are readily available. The production starts with ordering epitaxial wafers for 1.1μm, processing the wafers using standard semiconductor techniques to produce laser diode bars, and packaging the bars. After testing the laser diode bars, the emitters must be coupled to a single optical fiber, that will be connected to the “puck’ shape cover. The optical properties of the laser diode source must be tested before it is being integrated into the LASPT device. The cost of these steps is given in Table II.

2.4 LASPT System Integration and Testing

Finally the LASPT device is fabricated by integrating the three sub-system into a robust package, that can withstand the harsh mechanical/weather/electrical condition in which it will be operated. The LASPT device has to be tested for mechanical integrity and for its performance. The parameters to be measured are voltage holding, rise time, peak current and change of current in time (dI/dt). The estimate cost for these tasks is shown in Table II.

3.0 LASPT Production Cost Projections

In order to estimate the cost production of LASPT devices we have developed a Work Breakdown Structure (WBS), shown in Table I. We have estimated the cost of each element in the WBS and it is shown in Table II. For small volume production (about 100 units) the production cost is estimated to be $1,202/unit. For large volume production this cost will be reduced to about $700/unit.

4.0 Summary

All the basic technologies and processes that are required to fabricate LASPT devices are readily available. There will be, however, the need to develop some specific devices and processes for LASPT production, which will require some non-recurring expenses. The production cost will depend on the specific application, in particular the type of the light source that is needed to activate the LASPT device. As long as the light source can be a laser diode the estimate cost of an LASPT device is in the range of $700-$1,200 pending on the production quantity.

Table I: Workbreak Down Structure for LASPT Fabrication

1.0 Switch

1.1 Order thyristor
1.2 Fabricate Openings
1.3 Process thyristor
1.4 Test thyristor

2.0 "Puck" Shape Cover

2.1 Fabricate metal cover
2.2 Order fibers
2.3 Integrate fiber with cover
2.4 Etch fiber
2.5 Test Cover

3.0 Laser Source

3.1 Order wafers and fabricate lasers
3.2 Package lasers
3.3 Couple fibers
3.4 Order laser electronics
3.5 Test laser performance

4.0 System Integration/Testing

4.1 Laser/Switch/Cover integration
4.2 LASPT testing

Table II: LASPT Cost Production Projections

	Material ($)	Labor ($)	Total ($)
1.0 Switch			
1.1 Thyristor	250		
1.2 Grooves fabrication		40	
1.3 Thyristor processing		20	
1.4 Testing		20	
Sub-total	250	80	**330**
2.0 "Puck" Shape Cover			
2.1 Metal cover	50		
2.2 Fibers	1		
2.3 Fiber/Cover Integration		40	
2.4 Etch Fiber	1	20	
2.5 Test Optical Properties		20	
Sub-total	52	80	**132**
3.0 Laser Source			
3.1 Wafer/Processing	100	100	
3.2 Laser Packaging	10	50	
3.3 Fiber coupling		100	
3.4 Laser Electronics	100	40	
3.5 Test laser diode		40	
Sub-total	210	330	**540**
4.0 System Integration/Testing			
4.1 Laser/Switch Integration	80	80	
4.2 Testing		40	
~~Sub-total~~	~~80~~	~~120~~	**~~200~~**
Total			**1202**